

Linking the Dynamics of Cognitive Control to Individual Differences in Working Memory Capacity: Evidence From Reaching Behavior

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Abstract:

We used a technique known as reach tracking to investigate how individual differences in working memory capacity (WMC) relate to the functioning of two processes proposed to underlie cognitive control: a threshold adjustment process that temporarily inhibits motor output in response to signals of conflict and a controlled selection process that recruits top-down control to guide stimulus-response translation. Undergraduates (N = 135) performed two WMC tasks (updating counters and symmetry span) and a reach-tracking version of the Eriksen flanker task. Consistent with previous research using button-press flanker tasks, WMC significantly correlated with response time (RT) performance, with higher WMC scores corresponding to smaller congruency effects. Given that RTs reflect the combined functioning of multiple processes underlying cognitive control, we interpreted this effect to reflect a general link between WMC and both the threshold adjustment process and controlled selection process. We also found a significant association between WMC and participants' reach trajectories, with higher WMC scores corresponding to more direct reach movements on incongruent trials involving stimulus-response overlap with the preceding trial. We interpreted this effect to reflect a more specific link between WMC and the functioning of the controlled selection process. We discuss the observed links between WMC and cognitive control in relation to the unity and diversity of executive functions framework and in relation to the role of prefrontal and striatal dopamine in supporting adaptive cognitive control.

Keywords: cognitive control | flanker task | inhibitory control | reach tracking | working memory capacity

Article:

Working memory capacity (WMC) and cognitive control are central constructs in contemporary psychological research and theory. Broadly speaking, WMC refers to how robustly an individual can actively maintain and manipulate information in memory, whereas cognitive control refers to an individual's capacity to align their ongoing thoughts and actions with their current goals and context. Individual differences in WMC have been linked to a wide range of abilities and

outcomes, including the allocation of visual attention (Bleckley et al., 2003, 2015), reading comprehension (cf., Arrington et al., 2014; Van Dyke et al., 2014), multitasking (Hambrick et al., 2010), moral judgments (Moore et al., 2008), and performance on college entrance exams (Turner & Engle, 1989). Similarly, individual differences in cognitive control have been linked to levels of mental and physical health, quality of life, and success in school and at work (for a review, see Diamond, 2013).

Given the important role that WMC and cognitive control play in supporting adaptive cognitive functioning, a central research focus in cognitive psychology has been to identify the extent to which these constructs are related. This question is most commonly addressed using a macroanalytic approach (Engle & Kane, 2004) in which participants complete multiple tasks designed to target the same underlying construct so that a factor can be extracted that captures shared variation across the tasks. This enables researchers to use structural equation models and variance partitioning methods to identify the extent to which factors corresponding to different constructs relate to one another. Research adopting this approach has revealed robust links between WMC and cognitive control, indicating that higher levels of WMC are correlated with better performance on cognitive control tasks (e.g., Chuderski, 2014; Colom et al., 2008; Kane et al., 2016; Redick et al., 2016; Schweizer & Moosbrugger, 2004; Shipstead et al., 2014; Unsworth et al., 2009, 2012, 2014), although some studies have failed to observe this association (Keye et al., 2009, 2013).

Two strengths of the latent-variable approach are that it (a) enables researchers to abstract away from method- and task-specific factors and (b) does not require researchers to adopt a specific theoretical framework concerning the cognitive and neural underpinnings of the association between WMC and cognitive control. That is, the approach can show whether cognitive constructs are related without stipulating how this relation is instantiated at the level of specific cognitive processes. To address the how question, researchers often adopt a microanalytic approach (Engle & Kane, 2004) that assesses individual-by-treatment interactions within a particular control task to allow inferences about the cognitive and neural processes underlying the association between WMC and cognitive control (e.g., Ahmed & de Fockert, 2012; Heitz & Engle, 2007; Meier & Kane, 2013; Meier et al., 2018; Morey et al., 2012; Poole & Kane, 2009; Redick & Engle, 2006; Unsworth et al., 2004, 2012).

In the current study, we adopted a microanalytic approach to investigate how individual differences in WMC relate to the functioning of two dissociable processes proposed to underlie cognitive control: a threshold adjustment process that puts the “brake” on behavior when signals of conflict are detected and a controlled selection process that “steers” top-down resources to support goal-driven stimulus-response (S-R) translation. In the following, we illustrate how the threshold adjustment process and controlled selection process function in the context of one of the most widely used measures of cognitive control, the Eriksen flanker task (Eriksen & Eriksen, 1974). Next, we review recent research that has used a technique known as reach tracking to target how these processes unfold over the course of a response (the within-trial dynamics of control) and are modulated by trial sequence effects in which qualities of a previous trial influence performance on the current trial (the cross-trial dynamics of control). Finally, we will discuss how individual differences in WMC might differentially relate to the functioning of these processes.

The Dynamics of Cognitive Control

In the flanker task, participants see a stimulus array consisting of a centrally presented target and surrounding distractors. On congruent trials, the target and distractors cue the same response (e.g., <<<<<), and the demands placed on cognitive control are minimal. On incongruent trials, the target and distractors cue competing responses (e.g., <<><<), and consequently, cognitive control is required to ensure that the appropriate S-R pair is executed. Individual differences in cognitive control are typically assessed in terms of the congruency effect, which is computed by subtracting participants' average performance on congruent trials from incongruent trials (e.g., $RT_{\text{Incongruent}} - RT_{\text{Congruent}}$).

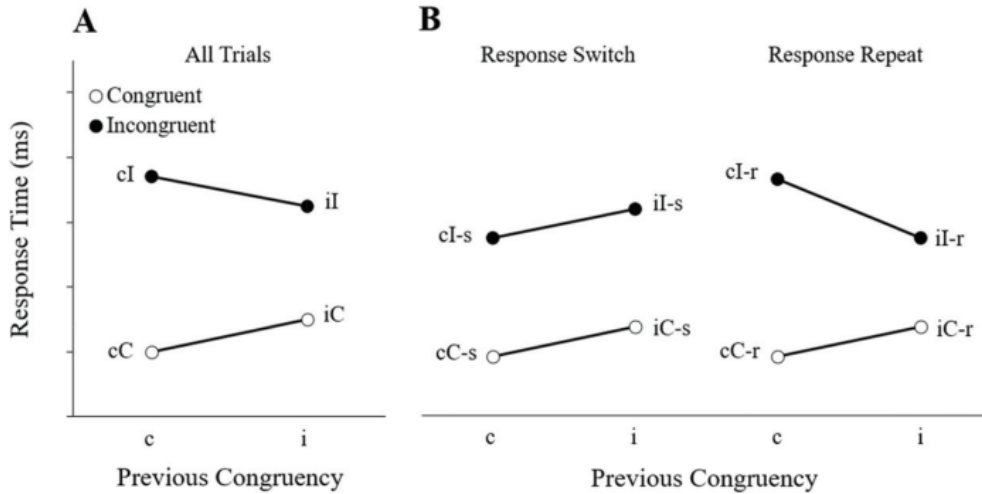
Performance on the flanker task has been proposed to reflect two processing pathways: a direct pathway that is sensitive to the entire stimulus array and a control-demanding pathway that supports goal-driven S-R translation by directing attention to the target (Botvinick et al., 2001; Ridderinkhof et al., 1995). On incongruent trials, conflict stemming from the target and distractors is registered by a monitoring process associated with the dorsal anterior cingulate cortex (dACC; Botvinick et al., 2001; Shenhav et al., 2013). This conflict engages two processes of particular relevance to the current study: a threshold adjustment process linked to the dACC and subthalamic nucleus (Aron et al., 2014; Frank, 2006; Frank et al., 2007; Ghahremani et al., 2018; Munakata et al., 2011) and a controlled selection process linked to the lateral prefrontal cortex (Shenhav et al., 2013). In response to signals of conflict from the monitoring process, the threshold adjustment process temporarily inhibits motor output, effectively putting a “brake” on behavior (Aron et al., 2014; Frank, 2006). Conversely, the controlled selection process is recruited to resolve the conflict registered by the monitoring process by “steering” attentional resources in favor of the control-demanding pathway, thereby facilitating goal-driven S-R translation. The flanker congruency effect observed in response times (RTs) can therefore be understood to reflect the costs associated with registering conflict, inhibiting motor output, recruiting top-down resources, and executing the appropriate S-R pair.

In addition to the congruency effect, substantial trial sequence effects are commonly observed in the flanker task. One such effect to receive a great deal of attention in the literature is the Gratton effect (also known as the congruency sequence effect), characterized by a reduced congruency effect on trials preceded by an incongruent trial (i.e., iC and iI trials, where the lowercase letter denotes the congruency of the previous trial and the uppercase letter denotes the congruency of the current trial) relative to trials preceded by a congruent trial (i.e., cC and cI trials). This effect, illustrated in Figure 1A, was originally observed in a two-alternative forced-choice (2AFC) version of the flanker task by Gratton et al. (1992). Subsequent research has revealed that the effect is specific to trials featuring the same response as the preceding trial (i.e., response-repeat trials; e.g., Mayr et al., 2003; Nieuwenhuis et al., 2006). In contrast to the Gratton effect observed on response-repeat trials ($cC-r < iC-r < iI-r < cI-r$, where -r indicates a response repeat), main effects of the current trial's congruency ($C < I$) and the previous trial's congruency ($c < i$) are observed in response-switch trials (Nieuwenhuis et al., 2006, Experiment 5), resulting in a different pattern of effects: $cC-s < iC-s < cI-s < iI-s$ (where -s indicates a response switch; see Figure 1B).

The Gratton effect observed in response-repeat trials in the flanker task has been attributed to feature integration effects, in which elements of the S-R pair formed on the previous trial impair or facilitate S-R translation on the current trial (e.g., Hommel, 2004; Hommel et al., 2004;

Nieuwenhuis et al., 2006). In 2AFC versions of the flanker task, response-repeat trials fall into one of two categories: partial-overlap trials, in which the stimulus array of the current trial differs from

Figure 1
Gratton Effect in 2AFC Flanker Task



Note. (A) Hypothetical data illustrating the pattern of effects observed by Gratton et al. (1992) in response times in a 2AFC flanker task. (B) Hypothetical data illustrating the pattern of response time effects observed by Nieuwenhuis et al. (2006, Experiment 5) when the effect of response type (switch vs. repeat) was taken into account. This figure was adapted with permission from Erb and Marcovitch (2018). 2AFC = two-alternative forced-choice.

that of the previous trial (iC-r and cI-r trials), and full-overlap trials, in which the stimulus array of the current trial matches that of the previous trial (cC-r and iI-r trials). According to the feature integration account of the Gratton effect, performance is impaired on partial-overlap trials because the S-R pair formed during the previous trial (e.g., <<<<< = LEFT) must be broken before the appropriate response (LEFT) can be bound to the stimulus array presented on the current trial (>>>>). Consequently, performance on partial-overlap trials is impaired, and RTs on iC-r and cI-r trials are longer than would otherwise be expected. Similarly, the account proposes that performance can be facilitated on full-overlap trials given that the appropriate S-R pair was recently formed and that activating one member of the pair (e.g., the stimulus) will automatically result in the activation of the other member of the pair. Performance on full-overlap trials is therefore facilitated, and RTs on cC-r and iI-r trials are shorter than would otherwise be expected.

In the context of the model of flanker task performance reviewed above, such feature integration effects can be understood to impact S-R translation along the control-demanding pathway. Importantly, all response-switch trials in 2AFC versions of the flanker task are no-overlap trials, in which both the stimulus array and the response of the current trial differ from the previous trial. Consequently, performance on these trials is not impaired or facilitated in the same manner as on partial-overlap and full-overlap trials, respectively.

Targeting the Within- and Cross-Trial Dynamics of Control With Reach Tracking

In recent years, researchers have used hand-tracking techniques to investigate the within- and cross-trial dynamics of cognitive control by measuring the spatial and temporal characteristics of

hand movements as participants perform congruency tasks by navigating a mouse cursor (mouse tracking; Incera & McLennan, 2018; Scherbaum & Dshemuchadse, 2019; Scherbaum et al., 2010) or by reaching to touch targets on a digital display (reach tracking; Erb & Marcovitch, 2018, 2019; Finkbeiner & Heathcote, 2016; Salzer & Friedman, 2019; Scorolli et al., 2014; Tillman et al., 2016). In addition to error rate and RT (time elapsed between stimulus onset and response completion), these techniques provide measures of initiation time (time elapsed between stimulus onset and movement onset), movement time (the time elapsed between movement onset and response completion), and curvature (the degree to which a participant's hand movement deviated from a direct path to the selected target). In a series of reach-tracking studies, Erb and colleagues (Erb & Marcovitch, 2018, 2019; Erb et al., 2016, 2017, 2018b, 2019; Erb, Smith, & Moher, 2020) have presented evidence indicating that initiation time and curvature can be used to target how the threshold adjustment and controlled selection processes function over the course of a trial and are modulated by trial sequence effects.

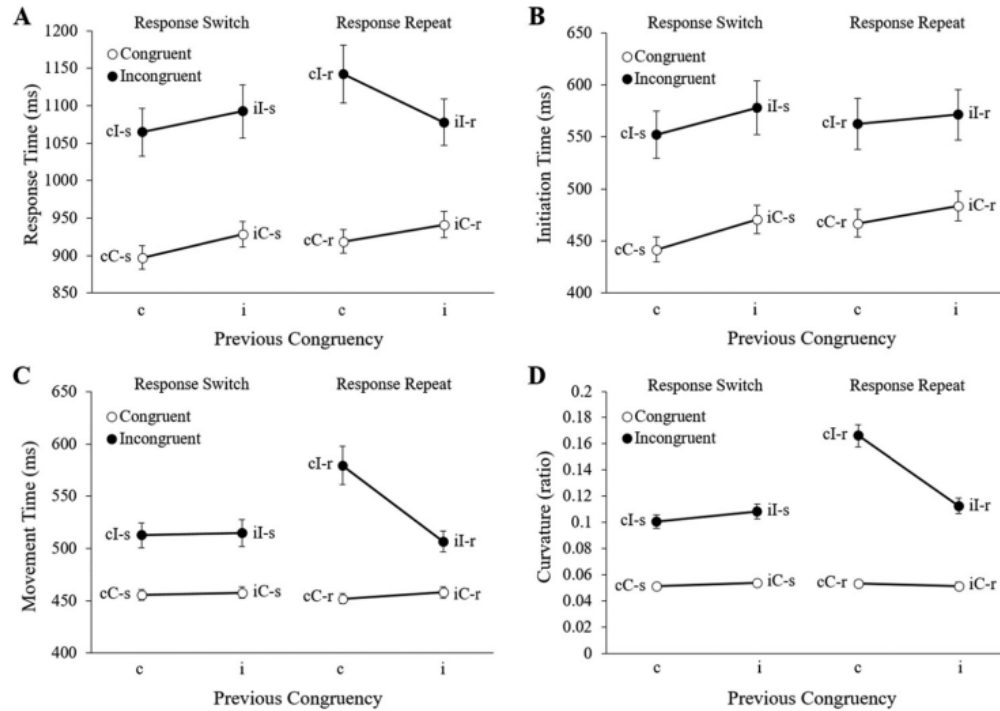
Specifically, Erb et al. (2016) proposed that initiation time could be used to measure the threshold adjustment process by indexing how long the “brake” was put on behavior before a response was initiated. In light of single-unit recording data collected by Sheth et al. (2012) suggesting that the threshold adjustment process was sensitive to the degree of conflict detected on both the previous and current trial, Erb and colleagues predicted that initiation times in congruency tasks would be elevated on incongruent relative to congruent trials ($C < I$) as well as on trials preceded by an incongruent trial relative to trials preceded by a congruent trial ($c < i$). Consistent with this prediction, Erb and colleagues observed significant main effects of current and previous congruency on initiation time in the flanker, Simon, and Stroop tasks (Erb & Marcovitch, 2018, 2019; Erb et al., 2016, 2018b). Notably, Erb and Marcovitch (2018) found that this pattern held across both response-switch and response-repeat trials in a 2AFC flanker task (see Figure 2B).

Building on previous hand-tracking research (Song & Nakayama, 2009; Spivey, 2007), Erb et al. (2016) further proposed that curvature could be used to target the functioning of the controlled selection process by indexing how active competing responses were over the course of a response. For example, a subject's reach to the target response on the right may be pulled toward the competitor response on the left, thereby increasing the curvature of the response trajectory. The results from a range of congruency tasks have supported this prediction as well (Erb & Marcovitch, 2018, 2019; Erb et al., 2016, 2018b, 2019). For instance, Erb and Marcovitch (2018) observed uniformly small reach curvatures on congruent trials, medium curvatures on incongruent trials not featuring S-R binding conflict (i.e., cI-s, iI-s, and iI-r trials), and large curvatures on incongruent trials featuring S-R binding conflict (i.e., cI-r trials; see Figure 2D).

Importantly, the patterns of effects observed in initiation times and movement times (the latter of which corresponded to the pattern observed in curvatures; see Figure 2C) combined to form the overall pattern of RT effects previously observed in 2AFC versions of the flanker task (see Figure 2A; e.g., Mayr et al., 2003; Nieuwenhuis et al., 2006). This finding indicates that the Gratton effect standardly observed in 2AFC flanker tasks is not a singular effect but rather the result of two distinct trial sequence effects that appear to stem from dissociable processes.

In addition to investigating the within- and cross-trial dynamics of cognitive control in the flanker task, Erb and colleagues (Erb & Marcovitch, 2018; Erb et al., 2018b) have used reach tracking to explore the developmental dynamics of control in the task by evaluating how performance varies between childhood and early adulthood. Their findings indicate that the threshold adjustment process reaches adult-like levels of functioning earlier than the controlled

Figure 2
Results From a Reach-Tracking Version of a 2AFC Flanker Task Collected by Erb and Marcovitch (2018)



Note. The study featured 45 participants from each of three age groups: 6- to 8-year-olds, 10- to 12-year-olds, and adults. Average (A) response time (initiation time and movement time combined), (B) initiation time, (C) movement time, (D) and reach curvature performance as a function of current congruency, previous congruency, and response type (response switch vs. response repeat) for all 135 participants. Error bars display standard errors. 2AFC = two-alternative forced-choice. This figure is presented with permission from Erb and Marcovitch (2018).

selection process. Further, curvature and movement time data from Erb et al. (2018b) and Erb and Marcovitch (2018) suggest that the age-related gains in cognitive control observed between late childhood and early adulthood in 2AFC versions of the flanker task are primarily driven by incongruent trials involving feature integration effects (e.g., cI-r trials).

The Current Study

The research reviewed in the preceding section indicates that initiation time and curvature can be used to target the functioning of two dissociable processes that fundamentally structure performance on congruency tasks, namely, a threshold adjustment process that temporarily puts the “brake” on behavior and a controlled selection process that “steers” response activations in favor of the task-relevant response. However, it is currently unknown the extent to which the links among WMC and cognitive control documented in previous studies (for example, Ahmed & de Fockert, 2012; Chuderski, 2014; Colom et al., 2008; Heitz & Engle, 2007; Kane et al., 2016; Redick & Engle, 2006; Redick et al., 2016; Schweizer & Moosbrugger, 2004; Shipstead et al., 2014; Unsworth et al., 2009, 2012, 2014) are driven by the functioning of these processes.

For instance, a number of studies have observed WMC-related differences on flanker-task performance. Redick and Engle (2006) observed smaller RT congruency effects in individuals with higher WMC relative to those with lower WMC in the attentional network test (Fan et al., 2002), which presents an arrow version of the flanker task under different cuing conditions. Similarly, Unsworth et al. (2012) used an arrow version of the flanker task and found that individuals with higher WMC generated smaller RT congruency effects than did those with lower WMC. Further, Heitz and Engle (2007, Experiment 1) found that conditional accuracy functions on incongruent trials reached asymptote at shorter RTs for individuals with higher WMC than those with lower WMC, indicating that individuals with higher WMC focused their attention on the target stimulus more rapidly than did those with lower WMC. In contrast to these studies, Keye et al. (2009) reported a null effect of WMC on the RT congruency effect observed in a 2AFC flanker task. Interestingly, the researchers did observe a significant effect of WMC on accuracy, with higher WMC linked to higher error rates on incongruent trials.

The current study used a reach-tracking version of the flanker task to address two central aims. First, we sought to replicate the results of our previous research with the flanker task (Erb & Marcovitch, 2018; Erb et al., 2018b) with a larger sample size to confirm that the patterns of trial sequence effects observed across RTs, initiation times, movement times, and curvature are robust and replicable. Specifically, we sought to confirm that RTs would reveal main effects of current and previous congruency on response-switch trials but a Gratton effect on response-repeat trials; initiation times would reveal main effects of current and previous congruency across response-switch and response-repeat trials; and movement times and curvatures would reveal a Gratton effect on response-repeat trials but not response-switch trials. These predicted effects are presented in Table 1.

Second, we investigated the extent to which cognitive control–WMC associations reflect the functioning of the threshold adjustment process and controlled selection process, as indexed by initiation time and curvature, respectively. We first tested whether the interaction between WMC and current congruency (C vs. I) observed in button-press RTs is also observed in reaching RTs. If so, WMC scores and RT congruency effects should be negatively correlated such that higher WMC scores correspond with smaller congruency effects. Next, we tested the extent to which the functioning of the threshold adjustment process is linked to individual differences in WMC by evaluating whether the effects of current congruency (C vs. I) and previous congruency (c vs. i) observed in initiation times vary with WMC. A positive or negative correlation between WMC scores and these congruency effects would indicate that the effect of conflict on the threshold adjustment process is more or less pronounced in individuals with higher WMC scores, respectively. Finally, we examined the extent to which the functioning of the controlled selection process is linked to individual differences in WMC by evaluating how the effect of current congruency (C vs. I) and interactions among current congruency and response repetition type (repeat vs. switch) vary with WMC.

Given that WMC is commonly linked to prefrontal regions (e.g., Kane & Engle, 2002; Klingberg et al., 2002; McNab & Klingberg, 2008), one might expect that individual differences in WMC would relate most closely to the functioning of the controlled selection process. On this view, individuals with a higher WMC may be better able to direct top-down resources in favor of the control-demanding pathway, resulting in more direct reach movements on incongruent trials. It is also possible that WMC is particularly important for guiding goal-driven S-R translation in the context of feature-integration effects. This possibility is supported by the developmental research reviewed above indicating that age-related gains in flanker performance observed

Table 1. Anova Results and Corresponding Bayesian Analyses for All Dependent Variables

Dependent variable	Effect	<i>F</i>	η^2_p	<i>p</i>	BF _{inc}	Predicted effect	Prediction match?
Response time	ci	29.87	0.18	<0.01	157,643		
	CI	432.93	0.76	<0.01	∞		
	SR	86.15	0.39	<0.01	1.34e + 14		
	ci × CI	22.64	0.14	<0.01	204		
	ci × SR	26.61	0.17	<0.01	1,678		
	CI × SR	0.49	<0.01	= .484	9.96		
	ci × CI 3 SR	17.21	0.11	<0.01	73.95		
	Switch						
	ci	58.60	0.30	<0.01	174006	c < i	YES
	CI	412.03	0.75	<0.01	∞	C < I	YES
Initiation time	ci × CI	0.10	<0.01	= .756	0		
	Repeat						
	ci	0.04	<0.01	= .848	0		
	CI	330.88	0.71	<0.01	6.00e + 15		
	ci × CI	33.72	0.20	<0.01	460	cC < iC < iI < cI	YES
	ci	104.43	0.44	<0.01	1.37e + 11	c < i	YES
	CI	199.97	0.60	<0.01	∞	C < I	YES
	SR	37.00	0.22	<0.01	2.65e + 7		
	ci × CI	0.24	<0.01	= .624	0.22		
	ci × SR	0.23	<0.01	= .634	0.21		
Movement time	CI × SR	41.27	0.24	<0.01	9,932		
	Switch						
	CI	284.48	0.68	<0.01	∞		
	Repeat						
	CI	107.12	0.44	<0.01	4.50e + 15		
	ci × CI × SR	1.46	0.01	= .228	0.03		
	ci	40.31	0.23	<0.01	5.36e + 14		
	CI	136.06	0.50	<0.01	∞		
	SR	30.44	0.19	<0.01	∞		
	ci × CI	37.80	0.22	<0.01	1.49e + 6		
Curvature	ci × SR	58.24	0.30	<0.01	1.46e + 8		
	CI × SR	61.90	0.32	<0.01	2.35e + 13		
	ci × CI × SR	24.59	0.16	<0.01	9,260		
	Switch						
	ci	0.02	<0.01	= .985	0.0,668		
	CI	60.52	0.31	<0.01	∞	C < I	YES
	ci × CI	0.10	<0.01	= .753	0.0,465		
	Repeat						
	ci	80.06	0.37	<0.01	6.45e + 11		
	CI	146.73	0.52	<0.01	6.00e + 15		
Curvature	ci × CI	50.16	0.27	<0.01	222,494	cC = iC < iI < cI	YES
	ci	81.63	0.38	<0.01	∞		
	CI	286.65	0.68	<0.01	∞		
	SR	73.99	0.36	<0.01	∞		
	ci × CI	120.75	0.47	<0.01	5.65e + 11		
	ci × SR	148.55	0.53	<0.01	1.75e + 12		
	CI × SR	139.23	0.51	<0.01	∞		
	ci × CI × SR	67.64	0.34	<0.01	367635		
	Switch						
	ci	1.12	<0.01	= .292	0.0,952		
Curvature	CI	217.98	0.62	<0.01	∞	C < I	YES
	ci × CI	3.42	0.02	= .067	0.1,097		
	Repeat						
	ci	169.23	0.56	<0.01	6.00e + 15		
	CI	290.46	0.68	<0.01	6.00e + 15		
ci × CI	146.97	0.52	<0.01	7.46e + 8	cC = iC < iI < cI	YES	

Note. ci = previous congruency; CI = current congruency; SR = response type (switch vs. repeat). We adopted an a level of .05 throughout. BFincl are inclusion Bayes factors and thus provide support for the inclusion of each term to the model; see main text for details. Dfs = 1,134 for all analyses. Predicted effects were based on the results of Erb and Marcovitch (2018).

For instance, a number of studies have observed WMC-related differences on flanker-task performance. Redick and Engle (2006) observed smaller RT congruency effects in individuals with higher WMC relative to those with lower WMC in the attentional network test (Fan et al., 2002), which presents an arrow version of the flanker task under different cuing conditions. Similarly, Unsworth et al. (2012) used an arrow version of the flanker task and found that individuals with higher WMC generated smaller RT congruency effects than did those with lower WMC. Further, Heitz and Engle (2007, Experiment 1) found that conditional accuracy functions on incongruent trials reached asymptote at shorter RTs for individuals with higher WMC than those with lower WMC, indicating that individuals with higher WMC focused their attention on the target stimulus more rapidly than did those with lower WMC. In contrast to these studies, Keye et al. (2009) reported a null effect of WMC on the RT congruency effect observed in a 2AFC flanker task. Interestingly, the researchers did observe a significant effect of WMC on accuracy, with higher WMC linked to higher error rates on incongruent trials.

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Given that WMC is commonly linked to prefrontal regions (e.g., Kane & Engle, 2002; Klingberg et al., 2002; McNab & Klingberg, 2008), one might expect that individual differences in WMC would relate most closely to the functioning of the controlled selection process. On this view, individuals with a higher WMC may be better able to direct top-down resources in favor of the control-demanding pathway, resulting in more direct reach movements on incongruent trials. It is also possible that WMC is particularly important for guiding goal-driven S-R translation in the context of feature-integration effects. This possibility is supported by the developmental research reviewed above indicating that age-related gains in flanker performance observed

between middle childhood and early adulthood are driven by trials that generate feature integration effects; it also appears consistent with the theoretical view that WMC reflects, in part, the ability to maintain and manipulate mental bindings, including S-R bindings (e.g., Oberauer, 2005, 2009; Oberauer & Hein, 2012; Oberauer et al., 2007). These views predict that reach curvatures will reveal an interaction among WMC, current congruency, and response repetition type such that individuals with higher WMC will generate more direct reach movements on incongruent response-repeat trials.

Alternatively, the links between WMC and cognitive control may reflect more general differences that apply across both the threshold adjustment process and the controlled selection process. For instance, the link between WMC and flanker task performance observed in button-press RTs has been attributed to individual differences in the ability to maintain a constrained focus of attention (e.g., Heitz & Engle, 2007; Poole & Kane, 2009; Unsworth et al., 2012). Differences in this ability could result in process-general effects by enabling individuals with a higher WMC to maintain a constrained focus, thereby minimizing conflict on incongruent trials. In this case, the links among WMC and cognitive control would not be specific to a particular measure such as initiation time or curvature but would instead be observed across multiple measures, including general measures that reflect the combined functioning of the various processes (e.g., RTs or accuracy).

METHOD

Preregistration and Data Availability

Portions of this study were preregistered through the Open Science Framework website on August 29, 2017 using the AsPredicted.org template (see <https://osf.io/qae49>). We present our preregistration along with accompanying comments in Section 1 of the online supplemental materials. We also specify which portions of the study were preregistered throughout the “Results” section. The data and analysis files for the current study are available at https://osf.io/6hz3a/?view_only=cca33bd4ee3e41098acfb0980c294dc5. Below, we report all data exclusions, manipulations, and measures in the study (Simmons et al., 2012).

Participants

A total of 135 adults were included in the final sample ($M = 19.3$ years, $SD = 2.1$; 83 women, 52 men). Participation in the study was limited to right-handed undergraduates 18 to 35 years of age with normal or corrected-to-normal vision, and it partially fulfilled an introductory course requirement. As noted in our preregistration, we intended to collect usable data from a minimum of 150 participants. Although we collected data from 160 participants, data from four participants were excluded for failure to meet our preregistered inclusion criteria: Data from three participants were excluded due to a failure to reach 75% accuracy or higher on the symmetry judgments in the symmetry span task, and data from one participant were excluded for not meeting the stated handedness criteria. Data from an additional 21 participants were excluded due to a programming error in the symmetry span task. After the programming error was detected, we extended testing to collect as many participants as possible during the academic calendar. Testing took place at the University of North Carolina at Greensboro (UNCG), a comprehensive state university and a

Minority Serving Institution for African American students. The institutional review board at UNCG approved the protocol.

Working Memory Measures

Eligible participants had previously completed a study investigating the links between WMC and mind wandering. As a part of this initial study, participants completed two working memory tasks, updating counters and the symmetry span (described below). The updating counters task was the second of seven tasks completed, whereas the symmetry span task was the sixth. At the conclusion of the initial study, participants received an informational flyer for the current study. Participants were then eligible to voluntarily enroll in the current study.

Updating Counters

Participants recalled numerical values of boxes after some were updated (Kane et al., 2016; modified from Lewandowsky et al., 2010). Each trial began with three to five boxes presented horizontally in the middle of the screen. There were three phases in each trial. The learning phase presented a digit (1–9) in each box in a random order. During the updating phase, some of the values were changed by presenting a digit to be added or subtracted (e.g., +3; –2). The updates were between –7 and +7; some boxes were updated multiple times and some not at all. Participants were instructed to remember the final updated value for each box, which was always between 1 and 9. During the recall phase, the boxes appeared on the screen, one of the boxes was randomly highlighted in red, and participants entered the final value of that box. Set sizes (three to five boxes) were crossed with number of updates (two to six) to generate a total of 15 trials. The dependent measure was the proportion of correctly recalled values out of 60.

Symmetry Span

Participants first saw a black-and-white patterned figure appear on an 8×8 grid and were told to verify whether the figure was symmetrical about the vertical axis (half were symmetrical). Participants were then presented with a red square within a 4×4 matrix, which they were to remember for later recall. At recall, participants were presented with an empty 4×4 grid, and they clicked on the location of the red squares they previously saw, in serial order. Each set length of two to five occurred twice in a random order for each participant. The dependent measure was the proportion of red squares recalled in the correct serial position (of 28).

Flanker Task

Participants completed a reaching version of the Eriksen flanker task (Erb & Marcovitch, 2018). The experiment was conducted using a rear-mounted projector to display the task on a Plexiglas screen, as in previous work (e.g., Erb et al., 2016; Moher & Song, 2013; Song & Nakayama, 2008b). The projector, screen, and an electromagnetic source were affixed to a wooden board that was mounted to a 91.4 cm by 152.4 cm table (see Figure 3A). The projected display on the Plexiglas screen was 38 cm by 50 cm. A 2 cm by 2 cm square marker was placed 27 cm in front of the screen. The square marker served as a starting marker from which participants initiated their

movements. Reach movements and response selections were measured at a rate of approximately 160 Hz with an electromagnetic position and orientation recording system (Liberty, Polhemus). In order to measure hand position, a small motion-tracking sensor was secured to participants' right index finger with a Velcro strap. The sensor was 2.3 cm long, 1.3 cm wide, and 1.1 cm high and weighed 3.7 g. The task was programmed in MATLAB (Mathworks).

Figure 3
Diagram of Experimental Setup

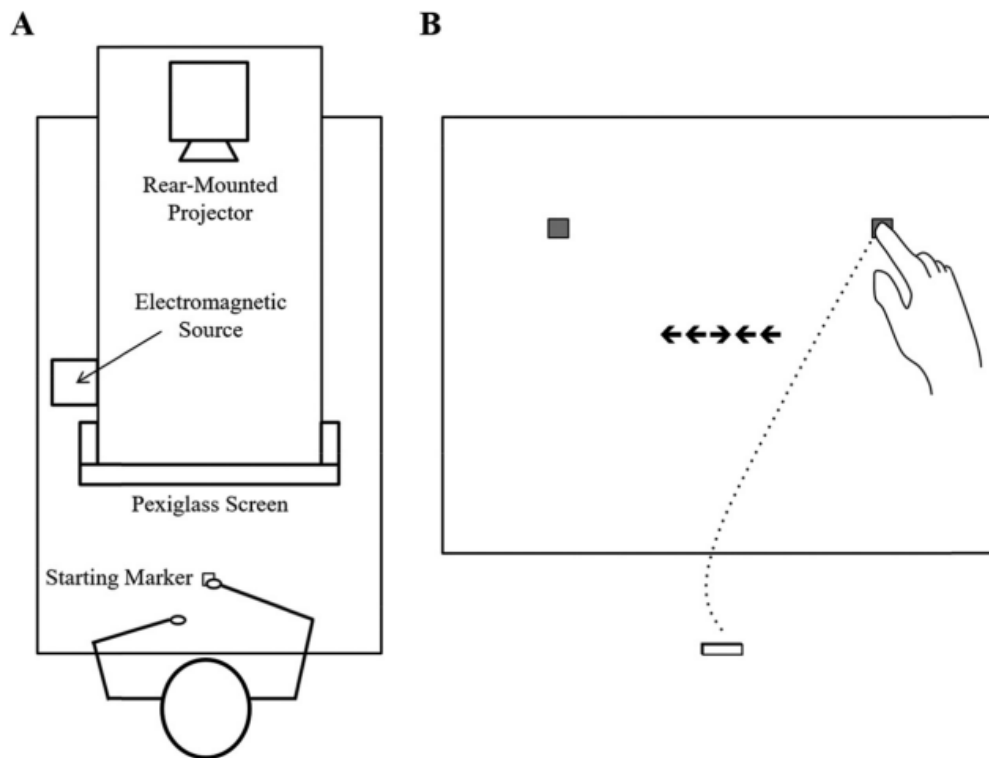


Figure 3. Note. (A) Diagram of experimental setup from aerial view. The task was displayed on a Plexiglass screen mounted upright on the table in front of the participant. All movements were initiated from a starting marker mounted on the table 27 cm in front of the screen. (B) Illustration of an incongruent trial in the flanker task from the perspective of the participant. This figure was adapted with permission from Erb and Marcovitch (2018).

Participants completed a two-response version of the flanker task in which an array of five gray arrows appeared in the center of the display following a fixation cue. Participants identified which direction the arrow in the center of the stimulus array was facing by touching one of two gray squares that measured 1.7 cm by 1.7 cm (see Figure 3B). Participants touched the right square for target arrows pointing right and the left square for target arrows pointing left. The center of each gray square was 11.5 cm from the top of the projected display, with one square located 11.25 cm in from the left side of the projected display and the other square located 11.25 cm in from the right side. Each array of arrows was 1.5 cm tall and 9 cm wide.

During each trial, a fixation crosshair appeared 1 s before the stimulus array, in the same location that the central target appeared, minimizing the demands placed on visual search. Each

trial initiated only after the participant's finger was resting on the starting marker for 1 s. If the participant's hand moved from this location before stimulus onset, the task paused and did not resume until the participant returned their hand to the starting marker for 1 s. Participants had up to 10 s to respond following stimulus onset. The stimulus array remained on the screen until the participant responded or the time limit was reached. A high tone sounded for correct responses provided in the allotted time (600 Hz for 200 ms). A low tone sounded for incorrect responses or responses that exceeded the allotted time (300 Hz for 200 ms).

Procedure

As in Erb and Marcovitch (2018), participants first completed a 9-point calibration sequence followed by 16 baseline trials that required reaching to a square that appeared alone at the top left or right of the screen. Participants then completed a practice block of 10 flanker trials before beginning the experiment. The experiment consisted of six blocks of 48 trials, for a total of 288 trials. Each block featured 24 congruent trials, in which the target and distractors cued the same response, and 24 incongruent trials, in which the target and distractors cued opposing responses. Trial presentation was randomized, and the correct response was evenly divided between the two response locations.

Before the experimental blocks began, participants were given the following instructions:

In this task, we want to see how quickly you can get through each round. You have a limited amount of time to respond, so it is important that you respond quickly. If you take too long to give a response or if you give the wrong response, you will hear a low tone. If you give the correct response under the time limit, you will hear a high tone.

Participants were then asked if they had any questions about the task. Before every block, the experimenter reminded participants (a) to perform the task quickly, (b) that it was "okay" to make some mistakes, and (c) to stay focused.

Data Processing

The processing procedures used in the current study were largely adapted from Moher and Song (2013) and matched those reported by Erb and Marcovitch (2018), so they were not data-dependent decisions (Gelman & Loken, 2014). Three-dimensional resultant speed scalars were created for each trial using a differentiation procedure in MATLAB. These scalars were then submitted to a second order, low-pass Butterworth filter with a cutoff of 10 Hz. Movement onset was calculated as the first point on each trial after stimulus onset at which hand movement speed exceeded 10 cm/s. Each individual trial was visually inspected as in previous work (Song & Nakayama, 2006, 2007, 2008b); for trials in which the default threshold clearly missed part of the movement or included substantial movement back to the starting point, thresholds were adjusted manually. Manual adjustments were most typically required when participants rapidly pulled their finger away from the screen after having touched a target or stopped entirely during their movement (e.g., after realizing that they had been moving toward the incorrect target). An average of 1.8% (SD = 3.0%) of experimental trials were adjusted manually for each participant (the adjuster was blinded to trial congruency and subjects' WMC scores).

Trajectories for calculating curvature were measured in two-dimensional xy space by automatically calculating a line from the start to the end point of the movement and measuring the

orthogonal deviation of the actual movement from that line at each sample. Curvature was defined as the maximum point of deviation in centimeters divided by the length of the line from the start to the end points of the movement in centimeters (following Desmurget et al., 1997; Moher & Song, 2013).

Results

We adopted an alpha level of .05 throughout our analyses unless otherwise stated. Error rates were at floor and occurred on less than 1% of trials; thus, they were not analyzed further. Following Erb and Marcovitch (2018), the first trial of each block was excluded from analysis given that these trials were not preceded by another trial. To control for posterror performance adjustments (e.g., Danielmeier & Ullsperger, 2011), all inaccurate trials and trials following an inaccurate trial were also excluded from analysis for each of the measures reported below. As planned in our preregistration, we then removed trials featuring outlying RTs using a recursive trimming procedure (Van Selst & Jolicoeur, 1994) that identified outliers for congruent and incongruent trials separately. This resulted in the exclusion of 0.5% of all congruent trials and 1.1% of all incongruent trials. Performance on each measure was analyzed with a series of analyses of covariance (ANCOVAs) featuring previous congruency (c, i), current congruency (C, I), and response type (repeat, switch) and the continuous WMC composite score WMC as a covariate. The analyses reported below reflect an average of 268.5 trials (SD = 8.9) per participant, with an average of 33.5 trials (SD = 1.1) in each of the eight cells resulting from the combination of the three within-subjects factors.

We present the results in four sections. Section 1 focuses on the experimental effects of previous congruency, current congruency, and response type to evaluate whether the effects observed previously by Erb and Marcovitch (2018) were replicated with a larger sample size. This will enable us to confirm whether the interpretation of the measures offered by Erb and Marcovitch is appropriate in the current study. Table 1 presents the analysis of variance (ANOVA) results for all effects.

In addition to our preregistered frequentist analyses, we also present the corresponding Bayes factor analyses in Table 1. We used the R package BayesFactor for the Bayesian analyses (Morey et al., 2015). All analyses were set to 10,000 iterations, with diagnostic checks for convergence via autocorrelation estimates for the parameters of interest and error terms for each term of our models. One chain per analysis was used for all analyses reported in the article (Lynch, 2007), with a thinning interval of 1 (i.e., no iteration was discarded). For the analyses of variance, the r scale was set to .5 for the fixed effects and .354 for the covariate (Liang et al., 2008; Rouder et al., 2012). Throughout the article, we report inclusion Bayes factors (denoted BF_{inc} herein). BF_{inc} is a specific type of Bayes factor that compares two classes of models, namely one with the term of interest and one without. In this context, BF_{inc} represents the change from the ratio of prior probabilities (prior odds) to the ratio of posterior probabilities (posterior odds), with or without the additional term. Therefore, BF_{inc} can be thought of as an index of the extent to which the data support inclusion of the term of interest given all models compared. A BF_{inc} ~ 1 indicates that the data does not provide support for inclusion (nor exclusion) of the term of interest, whereas a BF_{inc} above or below 1 indicates evidence for inclusion or exclusion, respectively. (Note that BF_{inc} bears no direct correspondence to p values.) All materials related to these Bayesian analyses are available on the Open Science Framework repository corresponding to this project. We also

provide the full set of results from the Bayesian analyses in Section 3 of the online supplemental materials.

Section 2 of the results focuses on how previous congruency, current congruency, and response type interacted with the WMC covariate. Results from the corresponding Bayes factor analyses are reported below as well as in Section 3 of the online supplemental materials. Section 3 presents exploratory analyses evaluating how individual differences in the correlation between initiation time and curvature might contribute to the links observed between WMC and cognitive control. Finally, Section 4 presents exploratory analyses focusing on the split-half reliability of central effects of interest.

Section 1: ANOVA Results

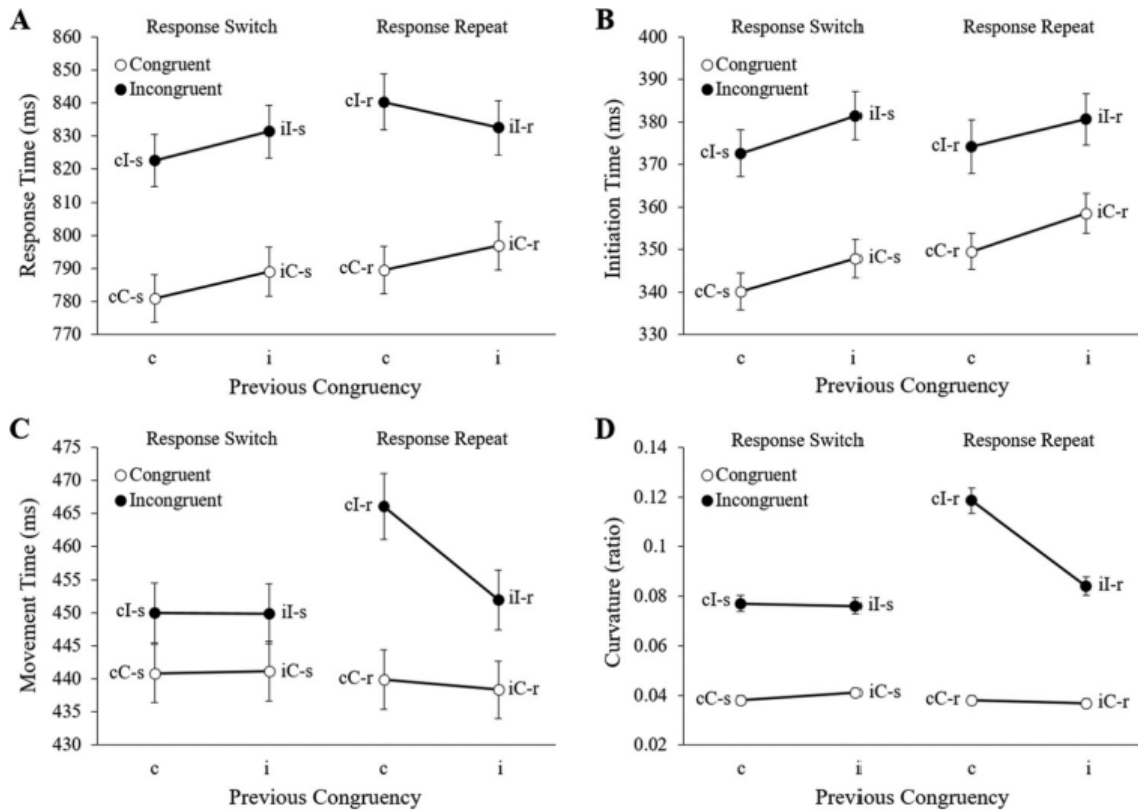
RTs (the time elapsed between stimulus onset and response completion) produced significant main effects of previous congruency, current congruency, and repetition type, as well as several significant interactions, including a three-way interaction (see Figure 4A). To account for this three-way interaction, we evaluated the effect of previous and current congruency on response-switch and response-repeat trials separately. Response-switch trials produced only significant main effects of previous congruency and current congruency, with shorter RTs on trials preceded by a congruent trial relative to those preceded by an incongruent trial ($c < i$) and shorter RTs on congruent relative to incongruent trials ($C < I$). Response-repeat trials, in contrast, produced a main effect of current congruency and a significant interaction between previous and current congruency. Follow-up tests confirmed that RTs were significantly shorter on cC-r relative to iC-r trials, as well as on iI-r relative to cI-r trials, with p values $< .001$. These results are consistent with the RT results reported by Erb and Marcovitch (2018), who also reported significant main effects of previous and current congruency on response-switch trials and a Gratton effect on response-repeat trials.

Also consistent with the results of Erb and Marcovitch (2018), initiation times were significantly shorter on trials preceded by a congruent relative to an incongruent trial ($c < i$) and on congruent relative to incongruent trials ($C < I$; see Figure 4B). Initiation times also produced a main effect of response type, as well as a significant interaction between current congruency and response type such that congruency effects were larger on response-switch than on response-repeat trials. However, follow-up tests indicated that current congruency effects were significant in both response-switch and response-repeat trials.

Movement times (time elapsed between movement onset and response completion) produced main effects of previous congruency, current congruency, and response type, as well as several significant interactions, including a three-way interaction (see Figure 4C). To account for this three-way interaction, we evaluated the effect of previous and current congruency on response-switch and response-repeat trials separately. Response-switch trials produced only a main effect of current congruency, with shorter movement times on C-s relative to I-s trials. The effect of previous congruency presented evidence for the null ($BF_{inc} = .067$), as did the interaction of previous and current congruency ($BF_{inc} = .047$). Response-repeat trials produced main effects of previous and current congruency, as well as a significant interaction. Follow-up tests indicated significantly shorter movement times occurred on iI-r trials relative to cI-r trials, $F(1, 134) = 85.70$, $\eta^2 = .39$, $p < .001$, $BF_{10} = 1.34e + 13$, but a nonsignificant difference between cC-r and iC-r trials, $F(1, 134) = 3.09$, $\eta^2 = .02$, $p = .081$, $BF_{10} = .427$.

Figure 4

Average (A) Response Time, (B) Initiation Time, (C) Movement Time, and (D) Curvature Performance as a Function of Previous Congruency, Current Congruency, and Response Type



Note. Error bars display standard errors.

Reach curvatures (a measure of the degree to which a participant's hand movement deviated from a direct path to the selected target) produced main effects of previous congruency, current congruency, and response type. Curvatures also produced a number of significant interactions, including a three-way interaction (see Figure 4D). To account for this three-way interaction, we evaluated the effect of previous and current congruency on response-switch and response-repeat trials separately. Response-switch trials produced only a main effect of current congruency, with smaller curvatures on C-s relative to I-s trials; the interaction between previous and current congruency on response-switch trials did not reach significance, $p = .067$. The effect of previous congruency presented evidence for the null ($BF_{inc} = .095$), as did the interaction of previous and current congruency ($BF_{inc} = .11$). These results are consistent with the curvature effects observed in adult participants by Erb and Marcovitch (2018), who also observed a significant main effect of current congruency in response-switch trials but no significant main effect of previous congruency and no significant interaction between previous and current congruency.

Also consistent with the curvature results of Erb and Marcovitch (2018), response-repeat trials produced main effects of previous and current congruency, as well as a significant interaction between the two factors. Follow-up tests indicated significantly smaller reach curvatures occurred on iI-r trials relative to cI-r trials, $F(1, 134) = 187.98$, $\eta^2 = .58$, $p < .001$, $BF_{10} = 1.30e + 24$. The

difference between cC-r and iC-r trials did not approach significance, $F(1, 134) = 1.36$, $\eta^2 = .01$, $p = .25$, $BF_{10} = .186$.

The experimental results replicated those observed by Erb and Marcovitch (2018). Overall RTs in the current study produced the same pattern previously observed in both button-press RTs and reaching RTs in 2AFC versions of the flanker task (Erb & Marcovitch, 2018; Mayr et al., 2003; Nieuwenhuis et al., 2006). Response-switch trials produced main effects of previous and current congruency, resulting in the following pattern of effects: $cC-s < iC-s < cI-s < iI-s$. Conversely, response-repeat trials produced a significant Gratton effect: $cC-r < iC-r < iI-r < cI-r$.

As predicted, initiation times produced main effects of previous and current congruency. The observed pattern of effects ($cC < iC < cI < iI$) has been proposed to reflect the threshold adjustment process, with conflict on incongruent trials resulting in elevated response thresholds that are carried over into the subsequent trial. Movement times and reach curvatures produced main effects of current congruency on response-switch and response-repeat trials. However, only response-repeat trials also produced a significant interaction between previous and current congruency in these measures, with no significant differences between cC-r and iC-r trials but enhanced performance on iI-r relative to cI-r trials. These patterns are consistent with the claim that movement times and curvatures reflect the functioning of the controlled selection process, with S-R binding on cI-r trials interfering with the controlled selection process's ability to form the appropriate S-R pair and marshal top-down support in favor of the appropriate response. Notably, the RT patterns reflected a combination of the patterns observed in initiation times and the patterns observed in movement times and reach curvatures. These findings provide further evidence that the Gratton effect observed in RTs in 2AFC versions of the flanker task reflects the functioning of both the threshold adjustment process and the controlled selection process (Erb & Marcovitch, 2018).

Section 2: ANCOVA Results

Table S1 in Section 2 of the online supplemental materials presents the full results of the ANCOVA. Here, we focus on WMC's main effects and interactions for each dependent measure. In our preregistration, we stated that initiation time and curvature were the primary measures of interest but that we would also evaluate performance on RTs, movement times, and error rates. However, we did not specify our predictions regarding which interactions would be significant in each of the measures. Consequently, we applied Bonferroni adjustments to account for the number of theoretically relevant comparisons made for each measure. Given that precise predictions regarding specific interaction effects were not preregistered, aspects of the following frequentist analyses and the entirety of the Bayesian analyses should be considered exploratory.

RTs produced a significant interaction between current congruency and WMC, $F(1, 133) = 7.45$, $p = .007$, $\eta^2 = .05$, with the size of the congruency effect decreasing with increasing WMC composite scores ($BF_{inc} = 18.47$). A closer examination of this interaction revealed two participants whose RT congruency effects were more than three interquartile ranges from the mean (see Figure 5A). Although we did not preregister that further outliers would be excluded from analysis, we performed exploratory analyses in which data from these two participants were excluded. These exploratory analyses revealed that the interaction between current congruency and WMC remained significant after the data from these two participants were excluded, $F(1, 131) = 4.16$, $p = .043$, $\eta^2 = .03$, $BF_{inc} = 2.21$.

Figure 5
Interaction Effects Involving WMC

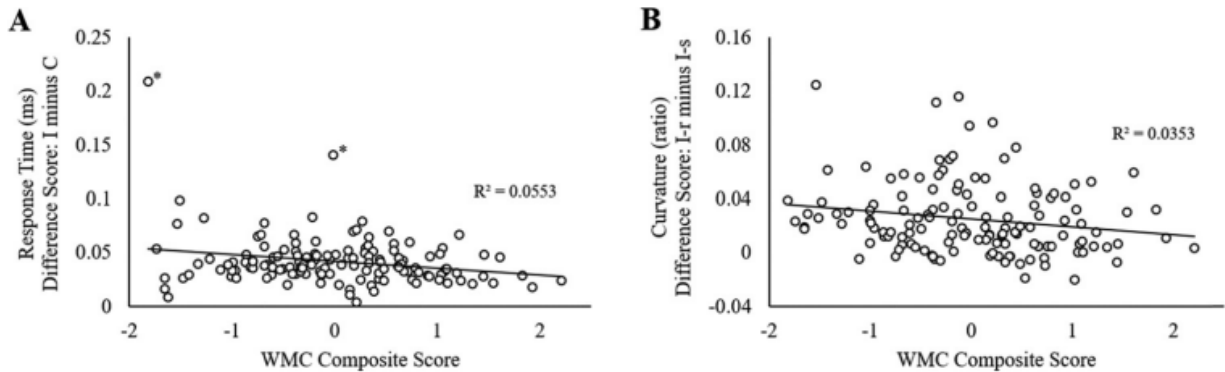


Figure 5. Note. (A) Scatterplot displaying the congruency effect (I – C) observed in response time for each participant as a function of their working memory capacity composite score (WMC). Asterisks denote two individuals whose congruency effect extended three interquartile ranges beyond the mean. The correlation between the size of the congruency effect and WMC, $r(133) = -.236$, 95% CI $[-.389, -.069]$, remained significant after these two data points were removed from analysis, $r(131) = -.175$, $[-.335, -.005]$, $p = .043$. (B) Scatterplot displaying the curvature difference observed between I-r and I-s trials (I-r – I-s) for each participant as a function of their WMC.

Two interactions were of specific interest for initiation time performance (WMC \times Previous Congruency and WMC \times Current Congruency). Consequently, a Bonferroni-adjusted alpha of .025 was adopted for our initiation time analyses. Initiation times did not reveal a significant interaction between WMC and previous congruency, $F(1, 133) = 2.31$, $p = .131$, $\eta^2 = .02$ (BFinc = .08) or between WMC and current congruency, $F(1, 133) = 3.52$, $p = .063$, $\eta^2 = .03$ (BFinc = 1.45).

Three interactions were of specific interest for curvature (WMC \times Current Congruency, WMC \times Current Congruency \times Response Type, and WMC \times Previous Congruency \times Current Congruency \times Response Type). A Bonferroni-adjusted alpha of .0167 was therefore adopted. Reach curvatures produced a significant interaction between current congruency, response type, and WMC, $F(1, 133) = 6.60$, $p = .011$, $\eta^2 = .05$ (BFinc = 4.66). Follow-up tests indicated that the interaction between response type and WMC was not significant for congruent trials, $F(1, 133) = .80$, $p = .37$, $\eta^2 < .01$ (BFinc = .04) but was significant for incongruent trials, $F(1, 133) = 4.87$, $p = .029$, $\eta^2 = .04$ (BFinc = 4.45). As is illustrated in Figure 5B, the difference in reach curvatures on I-r and I-s trials decreased as WMC composite scores increased, $r(133) = -.188$, 95% CI $[-.346, -.020]$, $p = .029$.

Section 3: Exploratory Analysis of Initiation Time and Curvature Correlations

The links observed between WMC and flanker performance may have reflected individual differences in the strength of association between initiation times and curvatures. For example, individuals with higher WMC scores may have taken longer to initiate their movements, possibly resulting in more direct reach trajectories and lower RTs overall. To evaluate this possibility of a trade-off between initiation time and curvature, we calculated the correlation between them for each participant. Initiation times were negatively correlated with curvatures on average ($M =$

-.165, $SD = .135$), but the strength of this correlation was not significantly correlated with WMC scores (.077), $p = .37$. Further, the correlation between WMC and the congruency effect observed in RTs remained significant when controlling for individuals' initiation time-curvature correlations (-.271), $p = .002$, as did the correlation between WMC and the difference between I-r and I-s trials observed in curvatures (-.172), $p = .047$. Consequently, it does not appear that these individual difference effects were strongly influenced by differential trade-offs between initiation times and curvatures.

Section 4: Exploratory Analysis of Split-Half Reliabilities

In order to identify the split-half reliabilities of effects of particular interest, we separated performance on odd blocks (1, 3, and 5) and even blocks (2, 4, and 6) and then computed the correlation of the effects observed in each subset of blocks. Following Whitehead et al. (2019), we corrected the split-half correlations using the Spearman-Brown formula (i.e., $2r/[1 + r]$). The congruency effects observed in RTs, initiation times, movement times, and curvatures revealed split-half correlations of .83, .87, .87, and .94, respectively. The effect of previous congruency observed in initiation times revealed a split-half correlation of .47. The differences between I-r and I-s trials observed in reach curvatures revealed a split-half correlation of .62.

We also evaluated the split-half reliabilities of the Gratton effects observed in RTs, movement times, and curvatures by subtracting the congruency effects observed on trials preceded by an incongruent trial (cC, cI trials) from the congruency effects observed on trials preceded by a congruent trial (iC, iI trials). RTs and movement times revealed nonsignificant negative Pearson correlations between the odd and even blocks (-.079 and -.024, respectively) and, consequently, were not evaluated using the Spearman-Brown correction. The Gratton effect observed in reach curvatures revealed a split-half correlation of .30.

Discussion

Individual differences in WMC and cognitive control have been linked to a range of abilities and outcomes, including overall levels of mental and physical health (e.g., Diamond, 2013; Evans & Kim, 2012; Evans & Schamberg, 2009). Consequently, a major focus of research in cognitive psychology has been to identify the extent to which individual differences in the two constructs are related. Research approaching this question from a macroanalytic perspective (Engle & Kane, 2004) indicates that the constructs are related, with higher levels of WMC correlating with better performance on cognitive control tasks (e.g., Chuderski, 2014; Colom et al., 2008; Kane et al., 2016; Redick et al., 2016; Schweizer & Moosbrugger, 2004; Shipstead et al., 2014; Unsworth et al., 2009, 2012, 2014; cf., Keye et al., 2009, 2013). However, the macroanalytic perspective offers a relatively limited view of how the constructs relate at the level of specific processes. The current study therefore adopted a microanalytic perspective to investigate how individual differences in WMC relate to the functioning of two processes proposed to underlie cognitive control: a threshold adjustment process involving the inhibition of motor output and a controlled selection process involving the recruitment of top-down control to guide S-R translation.

Results from a reach-tracking version of the flanker task revealed two significant interaction effects with WMC. Consistent with previous research using button-press versions of the task (e.g., Redick & Engle, 2006; Unsworth et al., 2012; cf. Keye et al., 2009), RTs showed a significant link between WMC and cognitive control such that individuals with larger WMC

composite scores generated smaller congruency effects. Neither initiation times nor movement times revealed significant interactions between WMC and current congruency, though both measures showed a trend consistent with the pattern observed in RTs, with higher WMC scores corresponding to smaller congruency effects. It is, of course, possible that the current study lacked sufficient power to detect these effects. However, the current data do not indicate that the link between WMC and the congruency effect observed in RTs was strongly driven by either initiation times or movement times given that the partial eta squared values observed in initiation time and movement were .03 and .02, respectively. Given that RTs reflect the combined functioning of multiple processes underlying cognitive control, this link can be described as process general in the sense that the effect was not specific to either the threshold adjustment process or the controlled selection process.

In contrast to RTs, reach curvatures showed a significant interaction among WMC, current congruency, and response type. Follow-up tests indicated that this interaction was driven by a significant correlation between WMC and the difference between curvatures on I-r and I-s trials (computed as I-r – I-s), with the size of this difference decreasing as WMC increases. This finding indicates that individual differences in WMC are related to how efficiently the controlled selection process functions on incongruent trials that involve feature integration effects, given that the S-R pairs formed on I-r trials either partially overlap (cI-r trials) or fully overlap (iI-r trials) with the S-R pair formed on the preceding trial, whereas S-R pairs formed on I-s trials feature a different stimulus array and response than the S-R pair formed on the preceding trial. Thus, the link between WMC and cognitive control observed in reach curvatures can be described as process specific in the sense that the link appears to reflect individual differences in one's ability to use the controlled selection process to execute the appropriate S-R pair on incongruent trials featuring the same response as the preceding trial.

What factors might underlie the process-general and process-specific links observed in RTs and curvatures, respectively? From a macroanalytic perspective, this question can be explored in terms of the unity and diversity of executive functions (EF) framework (Friedman & Miyake, 2004; Miyake & Friedman, 2012; Miyake et al., 2000). Factor analytic research within this framework indicates that performance across a wide range of EF tasks reflects three dissociable factors: (a) an updating-specific factor that is involved in monitoring and updating the contents of working memory, (b) a shifting-specific factor that is involved in switching between different tasks or mental sets, and (c) a common-EF factor that is involved in actively maintaining task-relevant information in order to bias lower-level processing (Miyake & Friedman, 2012).

Given that the common-EF factor is proposed to support active maintenance, and given that the link between WMC and flanker performance has been attributed to individual differences in one's ability to maintain a constrained focus of attention (Heitz & Engle, 2007; Poole & Kane, 2009; Unsworth et al., 2012), it is possible that the process-general effect observed in RTs in the current study reflected the functioning of the common-EF factor. On this view, an enhanced ability to maintain a constrained focus of attention (supported by the common-EF factor) resulted in less overall conflict on incongruent trials, leading to smaller adjustments of the threshold adjustment process and decreased demands on the controlled selection process. Similarly, given that the updating-specific factor is closely associated with working memory, it possible that the process-specific effect observed in reach curvatures reflected the functioning of the updating-specific factor. This interpretation of performance raises an intriguing avenue for future research—namely, using a factor analytic approach to identify how common and specific EF factors relate to the

functioning of the threshold adjustment process and the controlled selection process across a range of reach-tracking tasks.

The process-general and process-specific effects observed in the current study can also be interpreted to reflect dopamine's role in (a) stabilizing representations in the prefrontal cortex to increase distractor resistance and (b) flexibly updating representations in the striatum (for a review, see Cools & D'Esposito, 2011). Given that working memory has been linked to the functioning of the dopaminergic system (Cools & D'Esposito, 2011; Cools et al., 2008), and given that the link between WMC and flanker performance has been attributed to individual differences in one's ability to maintain a constrained focus of attention (Heitz & Engle, 2007; Poole & Kane, 2009; Unsworth et al., 2012), it is possible that the process-general effect observed in RTs in the current study reflected dopamine's role in supporting focused attention and distractor resistance via the prefrontal cortex. On this view, an enhanced ability to maintain a constrained focus of attention (supported by the prefrontal cortex) results in less overall conflict on incongruent trials, leading to smaller adjustments of the threshold adjustment process and decreased demands on the controlled selection process.

In contrast, the process-specific link observed in reach curvatures may have reflected dopamine's role in flexibly updating representations in the striatum. Research by Colzato and colleagues (Colzato et al., 2012, 2013) has indicated that levels of striatal dopamine play a crucial role in the binding and unbinding of stimulus and response features, particularly in instances in which the stimulus and response features of the previous trial partially overlap with those of the current trial. Thus, the process-specific link between WMC and cognitive control observed in reach curvatures on incongruent trials involving feature integration effects (i.e., full or partial overlap trials) may have reflected individual differences in the functioning of striatal dopamine.

The observation that individual differences in cognitive control are related to the ability of the controlled selection process to execute the appropriate S-R pair on trials involving feature integration effects dovetails nicely with research indicating that this ability undergoes a relatively protracted developmental trajectory (Erb et al., 2018b; Erb & Marcovitch, 2018, 2019; Hommel et al., 2011). Notably, age-related gains in the ability to bind and unbind stimulus and response features have been suggested to reflect changes in the same dopaminergic system linked to individual differences in adult performance (Hommel et al., 2011). Thus, variation in the functioning of this system may contribute to the developmental and individual differences in cognitive control observed in reaching behavior. For a review of how the dopaminergic modulation of cognition changes across the life span, see Li et al. (2010).

Processing Speed

A number of findings in the literature suggest that the links observed between WMC and cognitive control are driven at least in part by individual differences in processing speed. For instance, Keye et al. (2009) failed to observe a significant correlation between WMC and the size of the flanker congruency effect after accounting for individual differences in general RT performance. Additionally, Heitz and Engle (2007) found that individuals with higher WMC made fewer errors on congruent trials in the flanker task than individuals with lower WMC, indicating that WMC does not solely impact performance on incongruent trials. Finally, a number of previous studies have found that processing speed correlates positively with WMC (Danthiir et al., 2005; Schmiedek et al., 2007). It is therefore possible that the links between WMC and flanker

performance observed in the current study were driven by individual differences in processing speed.

To address this possibility, future research could control for individual differences in processing speed by collecting separate measures of the construct. However, this approach would require that the tasks used to assess processing speed not tap into the other constructs of interest. This requirement is problematic because the tasks frequently used to assess processing speed tap into cognitive control (Cepeda et al., 2013). Consequently, the conclusions that are formed about how cognitive control develops across the life span or differs among individuals can be influenced by which measures of processing speed are selected. Investigating the links among WMC, cognitive control, and processing speed therefore remains a significant challenge. As noted by Cepeda et al. (2013), addressing this challenge will require the development and standardization of processing speed measures that feature strong convergent and discriminant validity.

Effect Sizes and Sample Limitations

In comparison to a number of previous studies investigating the links between WMC and flanker performance, the effect sizes observed in the current study were relatively small. The interaction between WMC and current congruency observed in RTs had a partial eta squared of .05 that dropped to .03 after data from two participants were excluded. Similarly, the interaction between current congruency, response type, and WMC observed in reach curvatures featured a partial eta squared of .05. By contrast, Redick and Engle (2006) and Unsworth et al. (2012, Experiment 4) reported interactions between WMC and current congruency in RTs with partial eta squared values of .12 and .08, respectively. Notably, both of these studies featured an extreme groups design, with participants prescreened and selected from a larger population to be part of either a high-WMC or low-WMC group.

The results of the current study suggest that the effect sizes observed in extreme groups designs may not be representative of the relation between WMC and flanker performance in samples featuring a wider range of WMC scores. It is also important to note that, although our sample featured a relatively broad continuum of WMC scores, the sample was nevertheless restricted in the sense that participation was limited to college students 18 to 35 years of age. Consequently, the link between WMC and flanker performance may have differed in strength if a more representative subset of the population or a different age group had been sampled. Finally, although the sample size used in the current study was comparable to or larger than many of the previous studies investigating the links between WMC and flanker performance (e.g., Heitz & Engle, 2007; Keye et al., 2013; Poole & Kane, 2009; Redick & Engle, 2006; Unsworth et al., 2012), it should be noted (a) that we were unable to reach our preregistered target sample size of 150 participants and (b) that further research with larger sample sizes will help to clarify the robustness of the links observed in the current study.

Theoretical Accounts of the Congruency Effect

Performance on the flanker task has been interpreted in terms of both single- and dual-process models of attentional processing (Evans & Servant, 2020; White et al., 2011). Single-process models propose that attention functions like a spotlight that can be adjusted along a continuum from diffuse to focused (Eriksen & Eriksen, 1974). According to these models, the congruency effect occurs because the spotlight of attention is diffuse at the outset of incongruent trials,

resulting in the processing of the distractors before the spotlight is focused on the target. As noted by White et al. (2011), these models are classified as single-process models because decision behavior is driven by a single stream of evidence.

In contrast to single-process models, dual-process models propose an abrupt transition from a more diffuse form of attentional processing that encompasses the distractors to a more focused form of attentional processing that can be directed to select the target. The dual-pathway model of flanker performance outlined in the introduction is an example of a dual-process model as it proposes a transition from a diffuse form of attentional processing along the direct pathway to a more focused form of processing along the control-demanding pathway (Botvinick et al., 2001; Ridderinkhof et al., 1995).

Although we have framed our discussion of the flanker task along the lines of dual-process models, the results of the current study can be interpreted in terms of single-process models as well. On this view, reach trajectories can be interpreted to reflect the progressive focusing of attention onto the target rather than competition between a direct pathway and a control-demanding pathway. In previous work, Erb and colleagues (Erb & Marcovitch, 2019; Erb et al., 2017, 2018b) suggested that the controlled selection process reflects a competitive form of inhibition in which activation along the control-demanding pathway results in decreased activity along the direct pathway via lateral inhibitory connections (for a discussion, see Munakata et al., 2011). Given that single-process models do not involve transitions between different processing streams, this conceptualization of competitive inhibition would be inappropriate for single-process models. Consequently, a single-process view would require reinterpretations of select findings.

Although the current study was not designed to compare single- and dual-process models of flanker performance, we suspect that hand-tracking techniques might prove useful for comparing these models in future research. For example, researchers might be able to form competing predictions regarding the extent to which single- and dual-process models predict smooth versus abrupt changes in heading in versions of the flanker task that manipulate factors such as response bias and stimulus configuration (e.g., White et al., 2011). Additionally, recent advances in modeling techniques present powerful frameworks for empirically evaluating competing accounts of flanker performance (Evans & Servant, 2020). Future research should therefore explore how the informationally rich measures of performance afforded by hand tracking can be optimally integrated into ongoing modeling efforts. Such efforts would need to carefully consider the potential role of feature-integration effects and contingency learning effects (Braem et al., 2019).

Theoretical Accounts of the Gratton Effect

The Gratton effect has been attributed to a range of factors including feature integration (Hommel, 2004; Hommel et al., 2004; Nieuwenhuis et al., 2006), conflict monitoring (Botvinick et al., 2001; Egner et al., 2010; Ullsperger et al., 2005), and repetition expectancy (Erb & Aschenbrenner, 2019; Duthoo et al., 2013; Gratton et al., 1992). The pattern of effects observed in reach curvatures in the current study is most consistent with the feature integration account given that this account predicts that the Gratton effect will be observed in response-repeat trials but not response-switch trials in 2AFC versions of the flanker task (Nieuwenhuis et al., 2006). In contrast, the conflict monitoring and repetition expectancy accounts predict that a Gratton effect will be observed in both response-repeat and response-switch trials (for recent reviews of these accounts, see Duthoo et al., 2014; Schmidt, 2018). Importantly, none of the aforementioned accounts predict the pattern

of effects observed in initiation times. The results of the current study therefore underscore the importance of considering how dissociable processes underlying cognitive control can be differentially impacted by qualities of the preceding trials and, consequently, exhibit distinct cross-trial dynamics (for a detailed discussion, see Erb et al., 2019).

Consistent with previous studies investigating the relation between WMC and the Gratton effect in the flanker task (Keye et al., 2009; Unsworth et al., 2012), RTs in the current study did not show a significant interaction among WMC, current congruency, and previous congruency. Interestingly, Keye et al. (2009) did observe a significant interaction among these factors in the Simon task, with higher WMC scores corresponding to smaller interactions between current and previous congruency in RTs. This observation is well aligned with the feature integration account of the Gratton effect given that feature integration effects occur on a wider range of trials in standard 2AFC versions of the Simon task than in standard 2AFC versions of the flanker task (see Erb & Marcovitch, 2019). If WMC is particularly important for trials involving feature integration effects, as the curvature results of the current study suggest, it stands to reason that individuals with higher WMCs would generate smaller Gratton effects in the Simon task. This view is also consistent with reach-tracking research investigating developmental differences in the Simon task (Erb & Marcovitch, 2019), which found that the size of the Gratton effect observed in reach curvatures decreased significantly between middle childhood and early adulthood. Future research should therefore build on the current study by using reach tracking to explore the links between WMC and performance on the Simon task.

Delta Plots and Trial Sequence Effects

Researchers often evaluate performance on congruency tasks with delta-plot analyses by separating RT distributions for congruent and incongruent trials into five bins called quintiles. This enables researchers to identify how the size of the congruency effect differs among the bins and how the shapes of delta plots differ between conditions, tasks, age groups, or individuals (Ambrosi et al., 2019; Burle et al., 2005; De Jong et al., 1994; Heitz & Engle, 2007; Meier & Kane, 2015; Pratte et al., 2010; Ratcliff, 1979; Ridderinkhof, 2002; Stins et al., 2007; Unsworth et al., 2012; Xiong & Proctor, 2016). For example, this approach was used in the aforementioned study by Heitz and Engle (2007, Experiment 1) indicating that conditional accuracy functions reached asymptote at faster RTs for individuals with a higher WMC than those with a lower WMC. Unsworth et al. (2012) also evaluated flanker performance using delta-plot analyses and found that the effect of WMC was most pronounced in the slowest quintile of RTs. This finding was interpreted to reflect individual differences in one's ability to maintain a constrained focus of attention, with individuals lower in WMC more prone to lapses in constrained focus, resulting in larger congruency effects in the slowest quintile.

The results of the current study highlight the importance of considering how delta plots are structured by trial sequence effects. This point is well illustrated by the RT effects presented in Figure 4A. As this figure makes clear, different trial types will be differentially represented in the five RT bins, with a disproportionate number of cI-r trials represented in the slowest quintile. To the extent trial sequence effects are not taken into consideration in delta-plot analyses, the interpretation of such analyses may be limited. This point is particularly important to underscore when comparing delta plots for different congruency tasks given that the trial sequence effects observed in the Simon and flanker tasks differ substantially (Erb & Marcovitch, 2018, 2019). More generally, the results of the current study underscore the importance of evaluating how the effects

observed in delta-plot analyses correspond to the effects observed in reaching behavior (see Tillman et al., 2016).

Reliability of Effects

Split-half reliability analyses demonstrated significant correlations between performance on odd and even blocks for each of the primary effects of interest, including the congruency effects observed in RTs (.83), initiation times (.89), movement times (.87), and curvatures (.94). The effect of previous congruency on initiation times revealed a smaller split-half correlation (.47), as did the difference between I-r and I-s trials observed in reach curvatures (.62). Consistent with recent work investigating the split-half reliability of the Gratton effect observed in RTs (Whitehead et al., 2019), the current study observed a significant Gratton effect in RTs at the group level, but this effect did not prove to be a reliable measure of individual differences. Similarly, Scherbaum and Dshemuchadse (2019) found that the Gratton effect observed in a mouse-tracking version of the flanker task was not reliable as a marker of individual differences. These findings are not especially surprising given (a) our claim that the Gratton effect observed in 2AFC versions of the flanker task reflects the combination of two distinct patterns of trial sequence effects, (b) the observation that faster RTs on iI relative to cC trials are driven entirely by response repetition trials, and (c) our results indicating that individual differences in WMC are not significantly related to the size of the Gratton effect observed in RTs.

On our view, efforts to evaluate the split-half reliability of trial sequence effects will benefit from a careful consideration of how different processes underlying performance are modulated by different factors, including the level of conflict occurring on the previous trial, the occurrence of feature-integration effects, and a participant's level of preparedness for different trial types (Erb, 2020; Erb & Aschenbrenner, 2019). Although the terms Gratton effect and congruency sequence effect are used to refer to the observation that smaller congruency effects are observed on trials preceded by an incongruent trial relative to those preceded by a congruent trial, this usage may mask important differences of interest. For example, the terms could equally apply to instances in which RTs are slower on cI than iI trials, faster on cI than iI trials, or equivalent on cI and iI trials, so long as the difference between cC and iC trials is sufficiently large. The majority of congruency sequence effects reported by Whitehead et al. (2019), for instance, were driven by the difference between cC and iC trials, with certain tasks revealing equivalent RTs on cI and iI trials, others revealing descriptively faster RTs on cI relative to iI trials, and still others revealing descriptively slower RTs on cI relative to iI trials. An important direction for future research to explore therefore concerns the extent to which the threshold adjustment process and controlled selection process contribute to the various patterns classified as Gratton effects or congruency sequence effects in different tasks. We believe that this approach will help to address some of the current challenges surrounding the investigation of individual differences in cognitive control (Rouder et al., 2019; von Bastian et al., 2020).

Conclusion

The current study adopted a microanalytic approach to investigate how individual differences in WMC are reflected in the spatial and temporal characteristics of participants' hand movements in a reach-tracking version of the Eriksen flanker task. Relative to individuals with lower WMC, individuals with higher WMC generated smaller congruency effects in RTs as well as more direct

reach movements in the subset of incongruent trials that featured S-R overlap with the preceding trial. We interpreted these results to reflect the functioning of two processes underlying cognitive control: a threshold adjustment process that inhibits motor output in response to signals of conflict and a controlled selection process that recruits top-down control to guide S-R translation. Our findings raise fundamental questions concerning how these processes (a) relate to the factors identified within the unity and diversity of EF framework (Friedman & Miyake, 2004; Miyake & Friedman, 2012), (b) are linked to the functioning of prefrontal and striatal dopamine (Cools & D'Esposito, 2011; Cools et al., 2008), and (c) contribute to the effects observed in distributional analyses (Heitz & Engle, 2007; Unsworth et al., 2012).

In addition to shedding new light on the links between WMC and cognitive control, the current study highlights the advantages of using hand-tracking techniques to investigate individual differences in performance. Although techniques like mouse tracking and reach tracking are increasingly used to study topics such as attention (Moher et al., 2015, 2016), cognitive control (Erb et al., 2016; Erb, Smith, & Moher, 2020; Finkbeiner & Heathcote, 2016; Scherbaum & Dshemuchadse, 2019; Scherbaum et al., 2010, 2018), language processing (Dale & Duran, 2011; Farmer et al., 2007; Tomlinson et al., 2013), numerical cognition (Dotan & Dehaene, 2013; Erb et al., 2018a; Faulkenberry et al., 2015; Marghetis et al., 2014; Song & Nakayama, 2008a), and social cognition (Freeman & Ambady, 2009; Freeman et al., 2013, 2016); relatively few studies have used the techniques to target individual differences in performance (e.g., Freeman et al., 2016; Incera & McLennan, 2018; Sullivan et al., 2015; Szaszi et al., 2018). The results of the current study therefore contribute to a small but growing body of research demonstrating the value of incorporating hand-tracking techniques into individual differences research.

Footnotes

- ¹ Nieuwenhuis et al. (2006) did not report the effect of previous trial congruency on response-switch trials, but the first author confirmed that the effect was significant (S. Nieuwenhuis, personal communication, September 24, 2014).
- ² Readers interested in the feature integration account may also be interested in the binding and retrieval in action control framework presented by Frings et al. (2020). This framework builds on the feature-integration perspective by emphasizing that the processes of binding and retrieval are dissociable and may independently contribute to performance.
- ³ Note that iC-r trials did not exhibit larger reach curvatures relative to the other congruent trial types despite partially overlapping with the previous trial. Erb and Marcovitch (2018) suggested that this is because the response cued by the distractors on iC-r trials is the correct response. Consequently, engagement of the controlled selection process would not be expected to substantially alter one's hand trajectory.
- ⁴ Curvatures and movement times generally present similar patterns of effects in reach-tracking congruency tasks (Erb et al., 2019; Erb & Marcovitch, 2018, 2019). However, Erb and colleagues focused on curvature as a measure for targeting the controlled selection process because the spatial characteristics of reaching movements provide a more direct measurement of how active competing responses are over the course of a trial relative to the temporal characteristics of reaching movements (see Erb et al., 2016).
- ⁵ We suspect that this effect resulted from individuals with higher WMC being more responsive to feedback provided at the end of each block of trials. If individuals made fewer than four errors per block, they received feedback instructing them to respond faster (Keye et al., 2009). It is

possible that individuals with lower WMC were less responsive to this feedback, resulting in the seemingly counterintuitive interaction between WMC and congruency observed in accuracy.

⁶ The programming error in the symmetry span task was detected early in data collection and corrected. Given that the data from this task collected before the correction could not be used, we excluded all participants who completed the task before the error was corrected.

⁷ Movement times also failed to reveal significant interactions involving previous congruency or current congruency, p values $> .09$, B_{Finc} values < 0.30 .

⁸ It is important to note that the occurrence of feature integration effects varies across different versions of the Simon task. For example, the Simon task used by Keye et al. (2009) presented the imperative stimulus at one of two locations on each trial, whereas the task used by Meier and Kane (2015) presented the imperative stimulus at one of four or eight locations on each trial.

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